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Adaptation aux changements induits aux indices spectraux de l'audition spatiale chez l'humain.

par

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Résumé

Dans le cas de perte auditive, la localisation spatiale est amoindrie et vient entraver la compréhension de la parole et ce, malgré le port de prothèses auditives. La présente étude modifie la forme de l'oreille externe d'individus à l'aide de silicone afin d'induire des changements aux indices spectraux (HRTFs), similaires à ceux causés par des prothèses auditives, et d'explorer les mécanismes perceptifs (visuel, spectral, ou tactile) permettant d'alterner d'un nouvel ensemble à l'ensemble originel de HRTFs une fois les prothèses enlevées. Les résultats démontrent que les participants s'adaptent aux nouveaux HRTFs à l'intérieur de quatre séances d'entraînement. Dès le retrait des prothèses, les participants reviennent à leur performance originale. Il n'est pas possible de conclure avec les données présentes si le changement d'un ensemble de HRTFs à un autre est influencé par un des mécanismes de rétroaction perceptuelle étudié. L'adaptation aux prothèses perdure jusqu'à quatre semaines après leur retrait.

Mots-clés : Adaptation, Localisation spatiale, Indices spectraux, Perception, Plasticité.

Abstract

Spatial hearing contributes greatly to speech understanding in noisy environments. Hearing aids disturb all of the acoustic cues necessary for accurate sound localization and thus negate some of their benefits. This study addressed behavioral adaptation to changes in auditory spatial cues caused by changes similar to those induced by hearing aids. Spectral cues (HRTFs) were distorted by changing the shape of the outer ear with silicon molds. The present experiment was aimed at determining the perceptual modalities (visual, spectral or tactile) that might enable the switch from the modified to the original HRTFs once the molds were removed. Results indicate that participants were able to adapt within four training sessions. Participants immediately showed accurate sound localization when ear molds were removed. It was not possible to conclude whether the perceptual feedbacks had a major impact on the choice of the correct set of HRTFs to use. Adaptation to the modified HRTFs lasted weeks after their removal.

Keywords : Adaptation, Spatial localization, Hearing, Perceptual modalities, Plasticity.

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HRTF: Head-related transfer function

ms: milliseconds

À Frédéric Aubrais et Hugo Lagacé.

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Introduction

Le principal atout du système auditif est de pouvoir identifier et localiser des sons lointains. La perception spatiale des sons est fondamentale, en ce qu'elle permet à l'humain de s'orienter vers des objets situés à l'extérieur du champ de vision. Bien que souvent insoupçonnée, la localisation spatiale des sons est élémentaire à la compréhension d'une conversation, comme en témoigne l'effet *cocktail party* : en localisant la source d'un son, il est alors possible d'y diriger son attention, ou au contraire, de l'ignorer. La localisation des sons est ainsi possible grâce à deux catégories d'indices acoustiques disponibles à l'être humain : les indices binauraux et les indices monauraux.

Les indices binauraux – faisant usage de la différence entre les deux oreilles pour localiser un stimulus auditif – se subdivisent en deux types : les indices interauraux de temps et les indices interauraux d'intensité. Ces indices sont principalement responsables de la localisation sur l'axe horizontal (azimuth). La localisation de sons sur l'axe vertical (élévation) dépend quant à elle des encoches spectrales générées par la forme du pavillon auriculaire humain : la fréquence d'un son sera modifiée par la forme unique de l'oreille externe (pinna et concha, entre autres), la tête et le torse d'un individu, selon l'élévation d'un son. Ainsi, chaque son prendra une signature différente pour chaque élévation et ce, de manière personnalisée pour chaque individu. Pour cette raison, les indices monauraux sont nommés indices spectraux, ou encore *head related transfer function* (HRTFs).

Puisque la tête et les oreilles continuent de croître lors du développement de la personne, il est vraisemblable de croire que les indices spectraux sont également muables et dépendants de l'expérience, plutôt que présents dès la naissance. L'association entre l'origine spatiale d'un stimulus auditif et les différents indices acoustiques se doit donc être plastique. Alors que quelques recherches se sont intéressées à la plasticité de la localisation spatiale chez les animaux, peu se sont concentrées sur l'humain. Certains auteurs ont néanmoins été en mesure d'observer que la plasticité auditive est possible chez l'adulte (Javier and Schwarz, 1995; Hofman, van Riswick, et van Opstal, 1998; van Wanrooij and van Opstal, 2005). Il demeure toutefois nécessaire d'effectuer de plus amples recherches afin d'établir les circonstances de plasticité lors de la localisation spatiale chez l'humain.

Les dernières recherches menées à ce propos par Hofman, van Riswick, et van Opstal (1998) ont démontré qu'il était possible, suite à la modification du pavillon externe de l'oreille grâce à des prothèses de silicone, de réapprendre la localisation des sons sur l'axe de l'élévation en l'espace de trois à six semaines. Après le retrait de ces prothèses, la performance des participants à la tâche de localisation spatiale était aussi précise qu'avant le port des dites prothèses et ce, sans qu'une période d'adaptation ne soit nécessaire. Les auteurs ont alors conclu qu'il était possible pour l'humain d'encoder au moins deux ensembles de HRTFs et d'alterner d'un ensemble à l'autre. Le processus exact par lequel il serait possible de changer d'ensembles d'indices spectraux n'a pas été exploré depuis. Pourtant, malgré l'importance des HRTFs dans la vie quotidienne, peu à ce jour est connu à propos de l'encodage et le traitement des indices spectraux chez l'être humain. Le présent projet permettra de clarifier les mécanismes de rétroaction perceptuelle liée à la perception spatiale auditive.

Objectifs

Le principal objectif du projet est de comprendre comment les informations auditives sont encodées chez l'être humain, plus particulièrement lors de l'adaptation à de nouveaux HRTFs. Les résultats obtenus par Hofman, van Riswick, et van Opstal (1998) ont supporté l'adaptation auditive à un nouvel ensemble de HRTFs chez l'humain, sans toutefois pouvoir déterminer les mécanismes impliqués lors du transfert d'un ensemble de HRTFs à un autre. Dans cette suite d'idées, il est nécessaire dans un premier temps de répliquer les méthodes utilisées par Hofman, van Riswick, et van Opstal (1998) en employant des prothèses de silicone pour induire un changement des HRTFs et donc dans la perception spatiale des sons sur l'axe de l'élévation. Le projet a alors trois objectifs distincts : 1) répliquer l'adaptation à de nouveaux indices spectraux en faisant appel à un échantillon plus large que démontré par Hofman, van Riswick et van Opstal (1998); 2) examiner le processus qui permet le transfert du nouvel ensemble à l'ensemble originel de HRTFs lors du retrait des prothèses; et 3) déterminer la permanence de l'adaptation au nouvel ensemble de HRTFs suite au retrait des prothèses. Les résultats permettront de connaître quels sont les mécanismes liés à la transition d'un ensemble d'indices spectraux à un autre.

Hypothèses

Hypothèse 1. La première hypothèse atteste que la prothèse de silicone modifiera les indices spectraux des participants, réduisant alors leur précision dans la localisation spatiale des sons sur l'axe de l'élévation, tel qu'observé par Hofman, van Riswick et van Opstal (1998). Il est supposé que la perception sur l'axe de l'élévation sera d'abord compressée sur le plan horizontal, avant de progressivement se rétablir. Il est alors prédit que la moyenne des performances des participants du point de vue de l'élévation lors du port des prothèses sera significativement plus éloignée de la source réelle du son comparativement à la performance normale. Il est également prédit que la variance des réponses à la tâche de localisation spatiale lors du port des prothèses sera nettement plus élevée comparativement à la performance normale.

Hypothèse 2. En lien avec le deuxième objectif, soit d'examiner les mécanismes possiblement responsables du passage d'un ensemble de HRTFs à un autre, plusieurs pistes seront étudiées. Dans un premier temps, différents mécanismes perceptuels pouvant influencer la performance durant la tâche de localisation spatiale auditive seront examinés : la rétroaction visuelle, la rétroaction tactile, et la rétroaction spectrale. Il est stipulé que la rétroaction spectrale aura la plus grande influence sur la localisation spatiale des sons, compte tenu de l'importance des indices spectraux dans la localisation des sons.

Dans un deuxième temps, l'instantanéité à laquelle se produit le transfert d'un ensemble de HRTFs à un autre sera mesurée. Hofman, van Riswick, et van Opstal

(1998) ont conclu que dès le retrait des prothèses, les réponses des individus étaient de nouveau précises et ce, de manière instantanée. Toutefois, il est stipulé que le transfert d'une ensemble de HRTFs à un autre ne sera pas aussi instantané que le croit Hofman, van Riswick et van Opstal, mais nécessitera d'abord quelques stimuli afin de déterminer l'ensemble approprié de HRTFs à utiliser selon le contexte.

Hypothèse 3. Le présent projet évalue également la permanence des changements soumis par les prothèses de silicone en les replaçant aux oreilles des participants après diverses périodes de temps — soit trois jours, sept jours, deux semaines, ou quatre semaines — afin d'estimer la permanence de l'adaptation aux HRTFs induits. La troisième hypothèse prédit qu'il n'y aura pas de différences statistiquement significatives dans les performances dans le temps, quelque soit le délai écoulé depuis le retrait des prothèses.

Article

(à être publié)

Adaptation to modified spectral cues in spatial audition in humans.

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Adaptation to modified spectral cues in spatial audition in humans

Hearing loss, defined as “limiting the auditory information available to the listener, and in a frequently-dependant manner” (Noble, Byrne, & Lepage, 1993, p. 992), is one of the most prevalent chronic disabilities in Canada. Statistics Canada (2006) reported that 5.00 % of the Canadian population aged over 15 suffered from a hearing impairment, but only 19.00 % wore an assistive device such as a hearing aid (79.70 % of devices). While most research concluded that the majority of users were satisfied with their hearing aid (Wong, Hickson, & McPherson, 2003), many hearing aids in the United States were either returned (in 18.60 % of cases; Kochkin, 1999) or remained unused by the patient (in 12.40 % of cases; Kochkin et al., 2010). The low satisfaction and high return rates were explained by insufficient perceived benefit of the aid (Kochkin, 1999; Wong, Hickson, & McPherson, 2003).

One factor that is neglected in the fitting but likely reduces perceived benefit of hearing aids is spatial localization. Localizing sounds in space enables individuals to interact with their environment by providing important information as to what and where a sound is. Spatial hearing is essential in speech understanding, especially in a noisy environment: by knowing where a sound comes from, it is possible to suppress the unwanted signals and focus on the target (Kidd, Arbogast, Mason, & Gallun, 2005; Schneider, Li, & Daneman, 2007). Therefore, in a multi-talker context, such as a meeting, individuals with spatial hearing loss will show reduced speech understanding and lower social abilities (Byrne & Noble, 1998).

Furthermore, Noble, Ter-Horst and Byrne (1995) observed a positive correlation between severity of the hearing impairment and difficulty in sound localization. It is thus crucial that spatial localization is included in hearing aid design, especially considering that most hearing aids have an impact on localization because they fill in the external ear structure.

The hearing aid obstructs part of the concha, thus changing the spectral cues used in sound localization. While research demonstrated how wearing a hearing aid affected sound localization on the azimuth (horizontal) plane (Van den Bogaert, Klasen, Moonen, Van Deun, & Wouters, 2006), the main consequences of wearing an aid on spatial localization happened on the elevation (vertical) plane (Noble, Byrne, & Lepage, 1993). Hearing aids distort higher sound frequencies by reducing the external ear surface (Parseihian & Katz, 2012). These frequencies (between 4 and 10 kHz) carry the cues used by the auditory system to extract sound source elevation (Hebrank & Wright, 1974). Fortunately, humans can adapt to changed spatial cues and recalibrate elevation perception.

Hofman, van Riswick and van Opstal (1998) demonstrated that humans were capable of adaptation to altered spectral cues. Their experiment consisted of changing the ear shape by the use of silicone molds in order to test the plasticity of the human auditory cortex in learning a new set of head related transfer function (HRTFs). Although the spatial localization on elevation was compressed on the horizontal axis at first, the participants' performance slowly recovered within three to six weeks. Surprisingly, the participants' accuracy when the molds were removed was as precise as before wearing the molds, without any after effect being observed. For this reason, the authors concluded that the new set of HRTFs did not interfere with the original spectral cues representation, but was rather "more like acquisition of a new language than other form of sensory adaptation" (Hofrman, van Riswick, & van Opstal, 1998, p. 419). Their findings raised many questions as to how does the auditory cortex chose the right set of HRTFs, and how long does this adaptation persist. Knowledge of mechanisms related to the adaptation to changes in auditory cues is essential for improving hearing aid user training and will contribute to reducing the number of returned hearing aids and thus the cost of hearing aids. It may also guide hearing aid design in minimizing the distortion of acoustic cues.

Hypothesis 1

The first goal of the present study was to determine the course of adaptation over time to new HRTFs induced by silicone molds inserted on participants' ears (Fig. 1A). The participants then underwent a regular routine of spatial localization tasks to measure their progression. In order to shorten the adaptation time required to adapt to the molds, a spatial localization training task requiring head movements was used daily. Indeed, Parseihian and Katz (2012) observed that when using a localization task combining perception and action, adaptation to non-individualized HRTF could be achieved within three sessions of 12 minutes. Head movements were therefore used as the action component of the task here, since they facilitate spatial localization by providing different binaural cues for the same sound location (Perrett & Noble, 1997). Quickened by the training sessions, the adaptation was expected to follow a power-law learning curve (Yelle, 1979), a corrected version of the exponential curve. It was therefore expected that once the molds were inserted, the performance gain of the participants would be largest during the first few sessions, before reaching a plateau.

Hypothesis 2

The second goal was aimed at exploring the perceptual processes that are responsible for the seemingly instantaneous change – later referred to as switch – from the newly-learned spectral cues back to the original HRTFs when taking off the molds. Hofman, van Riswick, and van Opstal (1998) suggested that higher cognitive processes might not be involved in the adaptation to new HRTFs: focus was thus brought on perceptual mechanisms. The effect of three different types of perceptual feedback – visual, spectral and tactile feedback – on spatial localization was examined, to test three different hypotheses about what triggers the switch to the original HRTFs. Visual feedback indicates the correct sound source location, which may help to quickly select the correct set of HRTFs. Spectral cues present in the stimuli might help to distinguish between two sets of HRTFs and distorting these cues would then delay the switch. The tactile feedback of not having the molds attached to the pinna may trigger the switch to the original HRTFs and removing that feedback would delay the switch. Based on the facilitation effect of the visual information on auditory spatial perception (Wallach, 1940; Lewald, 2002; refer to Shelton & Searle (1980) for another opinion), the predictions were that the visual feedback would have the strongest influence on spatial localization: visual feedback following the sound stimulus may improve the participants' localization accuracy by stimulating spatial memory. However, the spectral and tactile conditions would negatively affect the localization performance. As observed by Kumpik, Kacelnik, & King (2010), the localization performance was expected to be less accurate when the spectral information from a stimulus was distorted. Finally, whereas Fisher (1964) demonstrated that tactile information has little weight in localizing sounds, it is expected in the present experiment that the tactile feedback of presence or absence of molds in the ears may still cue the participant to select the correct set of HRTFs and thus interfere with the auditory information.

Hypothesis 3

The third goal was to test whether the switch between the set of cues is instantaneous as concluded by Hofman, van Riswich and van Opstal (1998) or whether participants would require the presentation of a few stimuli before being able to localize sounds with the correct set of HRTFs. In the latter case, the results should show a difference in the participants' performance within the first few trials, indicating a change of strategy in spatial localization.

Hypothesis 4

The fourth goal of the study was to explore the permanence of the adaptation by reinserting the molds on the participants' ears after a time period of three days, one week, two weeks or a month. It was hypothesized that the participants would retain the ability to use the learned set of HRTFs and perform equally well during the retest as during their last performance with the molds, independent of the amount of time passed since the removal of the molds.

Materials and Method

Participants

Thirty-five participants were recruited from a lab participant pool and advertisements posted on the university campus websites (see Annex I). They all provided written informed consent (Annex II) before participating in the experiment. All participants had normal hearing, except two who had slight hearing loss of 36 dB for high frequencies (8 kHz): however, their hearing loss did not impact on their localization skills for they performed similarly to the other participants. Due to the molds having no effect on some individuals, ten participants had to be excluded from the study. The remaining 25 participants (11 males) were aged between 20 and 33 years old (M = 25.68; SD = 3.90), with a mean education of 17.44 years (SD = 3.37). The majority had French (56.00 %) or English (32.00 %) as first language, compared to the minority who first spoke Chinese (4.00 %), Polish (4.00 %) or Spanish (4.00 %). The majority of the participants had a right hand (20 participants) and right eye dominance (15 participants). Almost half of the participants had corrected vision by the means of glasses or lenses (11 participants). Only three participants were color-blind. The majority (19 participants) were musicians with at least 3 years of experience, while others had none or limited knowledge in music. The participants received a monetary compensation for their participation. The experimental procedures conformed to the World Medical Association's Declaration of Helsinki and were approved by the local ethics committee.

Stimuli

Sound stimuli were 250 ms in duration and consisted of five bursts of 25 ms of pink noise. On- and offsets of the bursts were gated with 2-ms squared-cosine ramps. The stimuli were filtered digitally between 20 and 20 000 Hz using a 5th-order Butterworth filter. Stimuli were created afresh on each trial on TDT System 3 hardware (Tucker Davis Technologies, www.tdt.com), controlled by custom Matlab (The MathWorks, www.mathworks.com) scripts.

Loudspeaker setup

Behavioral testing was conducted in a hemi-anechoic room (Fig. 1B). Participants were seated on a comfortable chair with a headrest, located in the centre of a spherical array of 80 loudspeakers (Orb Audio, www.orbaudio.com), of which 37 loudspeakers were used in the experiment, covering from - 45° to + 45° in azimuth and elevation. The layout of the loudspeakers is shown in Figure 3. Loudspeakers were placed on two arcs: on the horizontal arc (0° elevation), 13 loudspeakers were evenly distributed (azimuthal angle between adjacent speakers of 7.5°), whereas 12 loudspeakers were equally positioned on the vertical axis (0° azimuth). Twelve more loudspeakers were symmetrically distributed in the quadrants created by the two arcs (angle between speakers of 22.5°). The distance between the loudspeakers and the centre of the participant's head was 90 cm. An acoustically transparent black curtain was placed in front of the loudspeakers to avoid visual location cues.

A laser pointer and a head-tracking sensor (Polhemus Fastrak, www.polhemus.com) were attached to the head of the participant with an elastic strip. The dot of the laser pointer on the curtain served as visual feedback for the head position. Participants indicated perceived sound locations by pointing the head towards the perceived sound source location. Head position and orientation provided by the tracker were used to calculate azimuth and elevation of indicated directions.

Overall procedure

On the first day, a Bekesy audiometry test was performed with a clinical audiometer (Interacoustics AC40, www.interacoustics.com) to insure that the participants had normal hearing for frequencies between 125 to 8000 Hz. The central idea of the experiment was to modify participants HRTFs and follow their adaptation to the new listening situation with sound localization tests. To test how participants were able to switch back to using their original HRTFs after the molds were removed, localizations test that obscured different perceptual feedbacks were used to discover the ones possibly involved in this switch. For that, participants were randomly assigned to one of three conditions: *control*, *visual*, or s*pectral* (see Localization tasks with perceptual feedback). Each participant also completed a *tactile* condition. During the first lab session of each participant, individual HRTFs (see HRTFs measurement) were acquired (Fig. 2A), as well as individual binaural recordings of the stimuli used in the free-field sound localization task, which were later used as stimuli in the tactile condition. The participant then performed three sound localization tasks, which served as baseline measures: the free-field sound localization task, the assigned localization task with perceptual feedback, and the tactile condition task. The participants repeated the three localization tasks once the molds were brushed onto their ears. The second set of HRTFs was then recorded to quantify the physical changes induced by the molds (Fig. 2B-C). Differences in performance in the free-field test before and after application of the molds were used to verify their effectiveness in distorting HRTFs (Fig. 3A-B).

Starting on the second day, the participants performed a daily routine of free-field localization tasks and training sessions, which was continued until localization performance stopped improving and the mean localization error was constant for three consecutive days, which happened within 10 training sessions for most participants. The participants then proceeded to the next phase of the experiment and performed three tests over three days. They first completed the tactile condition, using binaurally recorded stimuli presented over headphones while still wearing the molds. On the following day, they performed a regular free-field localization task and training session. On the third day, participants completed a free-field localization task, then removed their molds, and immediately performed another free-field localization task (control) or a localization task with perceptual feedback (visual or spectral), depending on their group condition.

The final phase of the experiment was aimed at verifying whether the ability to localize sounds accurately with the molds would persist after a delay of three days, one week, two weeks, or four weeks after molds removal. The participants then reinserted the molds and completed a free-field localization task.

HRTFs measurements

Participants' HRTFs were measured with and without ear molds in to quantify the distortions in spectral cues induced by the molds. HRTFs were measured using empirical transfer function estimates (Grassi, Tulsi, & Shamma, 2003). Chirps of 5-ms duration were presented 40 times from each loudspeaker and recorded with ER7-14C probe microphones (Etymotic Research, www.etymotics.com). The participants were instructed to stay immobile during the recordings.

Free-field localization task

Stimuli were presented from different directions in pseudorandom order. Participants indicated perceived sound directions with head movements. Each direction was presented five times, for a total of 185 trials per run. No feedback was given. At the beginning of a run, the participant was asked to sit and lean on a neck rest, so that the head was centered in the loudspeaker arch and the head-mounted laser pointed at the central loudspeaker (0° in azimuth and elevation). This initial head position was recorded and the participant had to return to this position with a tolerance of 2 cm in location and 2° in head angle before starting each trial. To start a new trial, the participant pressed a response button. If the head was correctly placed when the button was pressed, a stimulus was played from one of the 37 speakers. If the head was misplaced, a speaker located above the participant's head (Azimuth: 0°, Elevation: 82.5°) played a warning tone, alerting the participant that the head was not in the correct position. In general, warning tones were seldom played after the free-field localization baseline task since the participants underwent a training session and quickly understood the procedure:

thus, no warning tones that could cue on the correct set of HRTFs to use happened during the first trials after insertion or removal of the molds.

After a stimulus was played, the participant pointed the head (and the laser pointer) in the direction of the perceived sound source and pressed the response button to validate an answer. The metric used to measure the localization accuracy of each participant was the mean signed error (MSE), a measure of the average discrepancy between participant's responses and targets locations (Hartmann, 1983). The participants also completed a localization task to set their baseline date, according to their perceptual feedback conditions. Different stimuli – see Localization task with perceptual feedback – were used depending on the condition.

Ear molds

Following the localization tasks, silicone molds were applied to the concha of the participants to modify ear shapes and distort HRTFs. The molds were created by applying a fast-curing medical-grade silicon (SkinTite, www.smooth-on.com) in a tapered layer of about 3 to 7 mm thickness on the cymba conchae and the cavum conchae of the external ear (Fig. 1A). Behavioral consequences of the modified HRTFs were verified with free-field localization tests: the mean localization error had to be one time and a half larger compared to the baseline performance in order to meet the criterion for sufficient induced changes.

Training

The participants started their localization training routine the day after the molds were installed (Time 2 on Fig. 4). The training sessions were 15 min long and the procedure was similar to the one described by Parseihian and Katz (2012). A continuous train of pink-noise pulses was presented from a random speaker and the rate of the pulses depended on the angular difference between the sound direction and the participants' head direction: the smaller the difference, the faster the rate. Participants were instructed to identify the sound source location as fast as possible by pointing their head in the correct direction. Once the participants held their head in the correct direction for 500 ms, the stimulus was considered to have been found and automatically changed location to a different random loudspeaker more than 45° away from the previous one.

Localization tasks with perceptual feedback

To test for possible contributions of different auditory and visual cues to the process of regaining accurate sound localization after the molds were removed, the participants were divided into three groups and completed four versions of the sound localization task in which different cues were altered or removed from the stimulation. All participants completed the tactile condition, which tested whether the tactile sensation of not wearing earplugs vs. wearing them triggers the switch to the original HRTFs were investigated. This was achieved by presenting binaural recordings made with the original ear shape (unmodified spectral cues), previously recorded using in-ear probe microphones, via headphones (DT 990 Pro, europe.beyerdynamic.com) to recreate the listening situation with the participants' original ears while still wearing the molds. Participants were further assigned to the visual, spectral, or control condition.

In the visual condition, whether visual input plays a role in switching HRTFs was examined. In this condition, visual feedback was provided after each response by briefly blinking a light emitting diode (LED) at the location of the sound source to indicate the correct response. In the spectral condition, whether knowledge of the stimulus spectrum is necessary to revert to the original HRTFs was studied. For that, the spectrum of the stimuli was randomly modified on each trial (spectral roving) by randomly changing the band intensity by a sixth octave from 0 to 40 dB (Kumpik, Kacelnik, & King, 2010). Finally, the remaining third of the participants were assigned to a control condition that completed regular free-field localization tasks, without perceptual modifications. In all localization tasks with perceptual feedback, the sequence of sound directions in the first five trials was the same in the baseline and test measurements for a given participant, in order to analyze these trials separately under the assumption that the switch to the original HRTFs occurred within these first few trials.

Retest

To test the persistence of the adaptation to the new HRTFs after the removal of the molds, the molds were placed back in the participant's ear after a delay of three days, one week, two weeks, or four weeks after the initial removal. The participants then completed a final free-field localization task to measure sound localization accuracy with the reinserted molds.

Statistical analyses

An elevation gain was computed to quantify the participants' use of HRTFs cues by measuring the slope (linear coefficient) of the regression line through perceived vs. presented elevations (Hofman, van Riswick, & van Opstal, 1998). A repeated-measure ANOVA was used to test for changes in the elevation gain over time and contrasts verified the polynomial trend of the adaptation curve.

In order to investigate the possible contributions of different auditory and visual feedback to the process of regaining accurate sound localization after the molds were removed, the baseline conditions for each testing localization tasks were compared to the free-field localization baseline to eliminate variance due to the cue manipulation.

The mean signed error of responses were compared trial by trial within the tactile condition using a repeated-measure ANOVA, and within the control, visual, and spectral condition by means of a mixed 3*8 ANOVA to estimate the combined effect of perceptual feedback condition and trial number. The performances during tactile condition were contrasted from the other conditions by means of dependant t-tests since all participants completed the tactile condition. Another mixed 4*8 ANOVA analysed the signed mean error of trial by trial responses during retest according to the time elapsed after the test condition (three days, one week, two weeks, or four weeks).

Normality and homogeneity assumptions for every test were verified using Shapiro-Wilk's, Levene's and Mauchly's tests as implemented in SPSS (SPSS 20, www.ibm.com). The statistical significance level was set at $p < .05$. The coefficient r was used to calculate the effect size.

Results

Spectral cues were modified by inserting silicon molds into the participants' pinnae. HRTFs were compared with and without the molds to confirm the behavioral effect of the modification (Fig. 3). The elevation gain, computed as the slope of the regression line through perceived versus presented elevations (see Methods), significantly decreased once the molds were inserted ($M = 0.29$, $SD = 0.17$) compared to the baseline performance ($M = 0.82$, $SD = 0.16$; $t_{24} = 12.75$, $p < .001$, $r = .93$), equivalent to a decrease to 35.37 % of the baseline performance on average.

Fast adaptation to modified HRTFs

The spatial localization training combined perception and action in order to reduce the amount of time required to adapt to the modified HRTFs. The daily training sessions started the day after the insertion of the molds. During the training and free-field localization routine, two different patterns in performance emerged in the free-field localization task: either participants responded well to the training and their elevation gain improved, or they did not respond to the training and showed limited signs of adaptation. For this reason, participants were divided into two independent groups based on their level of improvement: a minimum of three consecutive days of improvement and a mean recovery of two-thirds of their baseline localization score by the fifth day of training sessions acted as cut-off score for adaptation vs. non-adaptation group.

The majority of participants (17 out of 25) gradually increased their localization skills (M = 0.68, SD = 0.18) to reach 82.44 % of their original performance (Fig.4A), whereas eight participants showed no improvement in localization performance (M = 0.40, SD = 0.24) after five days of training (Fig. 4B), with a mean recovery of 48.29 % of their original score. The adaptation group's localization accuracy changed significantly over training (elevation gain vs. localization session, $F_{2.118,\ 19.060} = 9.08$, $p = .001$), which was not the case of the non-adaptation group (elevation gain vs. localization session, $F_{7,\ 56} = 2.05$, $p = .064$). The time course of the adaptation group was best fit by a quadratic function, as revealed by polynomial contrasts (elevation gain vs. localization session, $F_{1,9} = 15.93$, $p = .003$, $r = .98$). Since subsequent testing required that participants had adapted to the modified HRTFs, participants who did not were excluded from further analyses. Five participants from the adaptation group later lost their molds before the end of the experiment, and were then excluded from future analyses.

No effect of spectral roving and visual feedback on baseline performance

Five participants lost their molds before the final section of the experiment: therefore, only 12 participants completed the perceptual conditions. To have a better understanding of the potential influence of perceptual feedback when taking off the molds, the effect of the feedback condition before inserting the molds must first be asserted by comparing the participants' assigned feedback spatial localization baseline task to their free-field baseline performance. There was no interaction between the feedback condition and the localization task sessions:

participants in the control (n = 5), spectral (n = 4), and visual (n = 3) conditions performed equally well during the assigned condition and the free-field baselines ($F_{2,9}$ = 0.81, p = .24). There was no significant effect of cue manipulation (visual, spectral or tactile) ($F_{2,9}$ = 2.27, p = .08) nor of localization session ($F_{1,9}$ = 0.03, p = .44) on performance.

All participants also completed the tactile condition, which emitted through headphones the previously recorded binaural stimuli. The tactile condition baseline tasks were completed before and after the molds were fit to the participants' ears, which were both contrasted to the participant's free-field localization baseline to verify the impact of the stimuli presentation through headphones on the spatial accuracy while wearing the molds. Elevation gain during the baseline test of the tactile condition differed significantly from the baseline free-field localization performance (elevation gain vs. localization session, $F_{2,16}$ = 11.74, p < .001, r = .95). As a matter of fact, participants were more accurate during the free-field baseline (M = 0.89, SD = 0.20) than during the tactile condition at baseline without the molds (M = 0.74, SD = 0.21) ($F_{1,8}$ = 15.99, p = .002, r = .99). Inserting the molds to the participant's ear (M = 0.66, SD = 0.19) did not change spatial accuracy during the tactile localization task with headphones compared to the tactile baseline task without the molds ($F_{1,8}$ = 1.64, p = .24).

No after effect of molds removal

To investigate the effect of tactile feedback on spatial accuracy, participants still wore their molds on their ears to get physiological information contradictory to the spectral cues received by the headphones. After the adaptation period, participants completed the tactile localization task while still wearing the molds which was compared to the initial tactile baseline performance with molds to examine the after effect of the mold adaptation. Participants localized sounds less accurately during the final tactile condition test (M = 0.71, SD = 0.11) compared to the tactile baseline localization task (M = 0.88, SD = 0.18) (elevation gain vs. localization session, $F_{1,10}$ = 10.70, p = .004, r = .96).

After removing the molds, the participants completed a localization task depending of their assigned feedback condition to test whether the nature of the perceptual feedback affected – positively for the visual feedback and negatively for the spectral roving condition – the performances after mold removal. Performances during the feedback condition test were compared to the free-field localization baseline to evaluate the after effect of taking off the molds. There was no interaction between the feedback conditions and the localization task sessions: performance in the control, spectral, and visual groups showed no differences between the free-field baseline and the assigned test condition ($F_{2,9}$ = 0.59, p = .29). Performance was not affected by the feedback condition ($F_{2,9}$ = 1.92, p = .10), nor was it affected by the localization session ($F_{1,9}$ = 0.43, p = .27).

Trial-by-trial performance after mold removal

The task performance when re-exposed to the original HRTFs was analysed trial by trial in order to test whether participants regained accurate localization – expressed here in terms of localization error in degrees – within the first few trials of the test. Due to having only three to five participants per trial in this analysis, results were noisy: the analyses were therefore limited to the first five trials of assigned condition performance (Fig. 5). There was no interaction between feedback conditions and trial number: the localization error did not differ significantly between the control, spectral, and visual conditions within the five first trials ($F_{8,36} = 0.35$, $p = .94$). Moreover, trial number (error by trial, $F_{4,36} = 1.31$, $p = .28$) and assigned condition (error by feedback condition, $F_{2,9} = 0.47$, $p = .64$) did not individually affect localization error. The performance during the tactile condition also did not differ within the first five trials (error by trial, $F_{4,40} = 0.83$, $p = .52$).

Adaptation persists for several weeks

Nine out of the 12 participants (5 males) who completed the previous phase of the experiment accepted to complete a retest session. After a delay of three days, one week, two weeks, or four weeks from the point in time when the molds were taken off, the participants completed a free-field localization retest to investigate the permanence of the induced HRTFs adaptation. There was no interaction between the retest delay conditions and the localization session: the performance between the different retest delays was similar to the participants' last performance with the molds – i.e. when fully adapted – and their retest localization task ($F_{3,5} = 1.40$, $p = .34$), no matter how long the delay was since the molds' removal. The elevation gain during the retest localization task was similar to the participants' last performance with the molds (elevation gain by localization time, $F_{1,5} = 1.39$, $p = .29$). Finally, the localization performance was independent of the amount of time passed since the mold removal: the elevation gains after three days, one week, two weeks, and four weeks were similar (elevation gain by retest condition, $F_{3,5} = 0.18$, $p = .90$).

The same trial-by-trial localization accuracy analysis as after mold removal was carried in order to investigate the instantaneity of the switch from the original HRTFs to the modified cues. There was no interaction between the retest delay condition and the trials: the retest delays and the trial number combined did not influence the localization error ($F_{27,45} = 0.82$, $p = .71$). Also, the localization error did not differ within retest condition when averaging across the first five trials (error by retest condition, $F_{3,5} = 0.097$, $p = .959$), or within the first five trials when averaging across conditions (error by trial, $F_{9,45} = 0.668$, $p = .733$).

Discussion

Silicone molds were fitted to participants' ears in an attempt to better understand adaptation to modified auditory localization cues. Four goals were pursued in the present study: 1) to determine the time course of the adaptation to modified HRTFs; 2) to check the possible perceptual mechanism responsible for the switch from modified to original spectral cues; 3) to investigate whether the switch is instantaneous or occurs within the first few stimulus presentations; and 4) to test the permanence of the adaptation.

Fast adaptation to modified HRTFs

Participants were divided into two groups, adaptation or non-adaptation group, based on their adaptation level. Even if affected by the molds insertion, the non-adaptation group showed limited improvement in their spatial localization performance. Those participants might not have responded well to the training, and more time might have been necessary in order to observe adaptation to the modified HRTFs. Indeed, the adaptation curve for the non-adaptation group showed a trend for improvement (p = .064, observed power = .74) that might have reached the statistical significance criterion in a larger sample (a sample size of n = 21 would yield a significant result, ceteris paribus).

In the adaptation group, the perception-action training involving head-movements reduced the time of adaptation from three to six weeks (Hofman, van Riswick, and van Opstal, 1998) to four training sessions of 15 minutes, comparable to results by Parseihian and Katz (2012). Apart from the explicit training, mere exposure to spatial sounds in the participants environment was sufficient to measurably increase elevation gain between the moment the molds were inserted into the participants' ears and the start of the training sessions on the following day (between Time 1 and Time 2 in Fig. 4A). Further, the adaptation curve was best fit by a quadratic curve. Overall, the curve showed considerable improvement in the first few days, before reaching a plateau, thus exhibiting the pattern of the expected power-law curve (Yelle, 1979). The adaptation further persisted over several weeks, as suggested by Hofman, van Riswick, and van Opstal (1998).

Effect of headphones on baseline performance

To interpret the effect of the different feedback conditions on localization performance once the molds were removed, it was first necessary to measure baseline sound localization performance (before molds were inserted) under the different feedback conditions. Contrary to expectations, baseline localization accuracy was not affected by the visual, spectral and control manipulations. The visual feedback might not have interacted with the auditory information since presented after the stimuli: the visual cue might then have had a limited facilitation effect on the elevation plane, if any, as suggested by Shelton & Searle (1980). The spectral roving might not have been severe enough to impair localization, because Kumpik, Kacelnik, and King (2010) showed that elevation localization is impaired by large amounts of spectral uncertainty. Participants were less accurate in the tactile condition, in which they were presented with binaurally-recorded stimuli over headphones. This was expected, because headphone simulations of external sound sources are technically challenging and do not work for all participants (Carlile, Jin, & Harvey, 1998; Carlile, Jin, & Van Raad, 2000; Wightman & Kistler, 1989). The performance changes reported here are most likely due to the variable quality of binaural recordings.

No after effect of mold removal

Since none of the feedback conditions affected performance, it is impossible to determine whether the visual or spectral information is important for choosing the correct set of HRTFs. As for the tactile condition, the differences between the last performance with the headphones and the baseline performance might be due to presenting the stimuli through headphones, and not the tactile feedback of the molds itself. The absence of any effect of perceptual feedback is likely due to insufficient sample size (3 to 5 participants per feedback condition, observed power = .30). Power calculations suggest that a group size of at least 41 participants is needed to detect these effects. Testing of additional participants is underway.

Trial-by-trial performance after mold removal

It was expected that the change from the set of modified HRTFs to the original cues would occur within the first stimulus presentations. Due to statistical analysis limitations arising from the small sample size, the number of trials examined was limited to five. Localization accuracy was comparable during the first few trials and during the remainder of the test, and there was thus no sign of large initial improvement that would signal a switch from an incorrect to a correct set of HRTFs. Thus, either the switch occurred instantaneously when the molds were taken off without requiring any sound input, or it happened during the first stimulus presentation. However, an initial improvement might be masked by the differences in localization accuracy between the different loudspeaker positions, which were not taken into account in the present analysis.

Limitations

Some limitations have been encountered during the present study. First, the material chosen for the molds caused some technical difficulties: while the Skin-Tite product was suitable for the experiment - i.e. the product remained attached to the skin until removal - the duration of the study and the participants' life habits (shower, sports, sleep patterns) tended to put too much strain on the silicone material. Several participants lost their molds or required intermittent repair of the molds. This problem might be overcome in using electronical devices to induced HRTFs changes instead of silicone molds. A second limitation was that the molds did not affect the behavioral performances for seven participants, even if HRTFs changed measurably in these cases. The lack of behavioral effect could be explained by the limited changes caused by the molds to make the external ear smaller: modifications might not have been sufficient to disrupt spatial localization. Anecdotally, participants who did not show behavioral effect tended to have very small ears and thus little surface area that could be used for the modification. Unfortunately, morphological measures of the pinna and concha were not taken in the present study. Future studies might reveal correlations between anatomical measures and susceptibility to HRTF modification.

Conclusion

The present study aimed to replicate Hofman, van Riswick and van Opstal's (1998) results in order to answer questions about the adaptation and permanence of modifications to spectral cues in spatial audition in humans. Though it is currently impossible to determine which perceptual processes might be involved in the HRTFs switch, the present findings greatly increase knowledge on spatial localization on the elevation plane that can be transferred to hearing aid design. First, the results further support research that previously demonstrated adaptation can be hastened either with training or information sessions (Kochkin, 1999; Wong, Hickson, & McPherson, 2003). Second, some individuals may not respond well to their hearing aids, just as some participants did not adapt to the new HRTFs during the study. Therefore, new hearing aids should be developped and additional support should be offered to these individuals in order to facilitate their adaptation to their new HRTFs. Third, the speed of adaptation combined to its level of permanence will bring hope to individuals with newly diagnosed hearing loss by the presence of long-term benefits in using a hearing aid. Nevertheless, more studies are required to improve hearing aids and to remove the painful process of poorly malfunctioning hearing aids, therefore ensuring a better future to the the aging population. As an example, additional research should further investigate the perceptual mechanisms responsible for the HRTFs switch in order to include all facilitating factors in the training sessions and ensure a better adaptation to the aids.

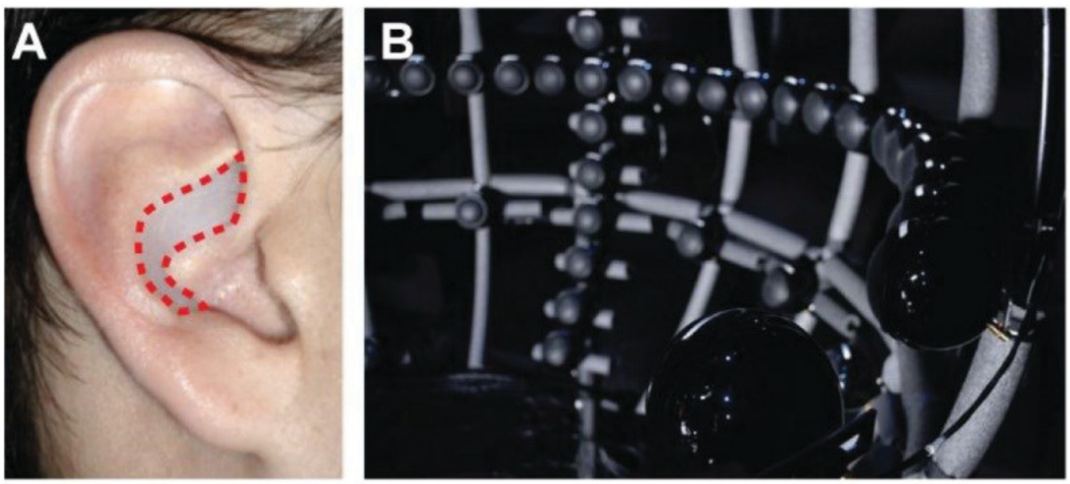


Figure 1. A) Skin-Tite silicone (red dotted line) molded to a participant's concha. The material is comfortable to wear and almost invisible. B) The BRAMS 80-loudspeaker array.

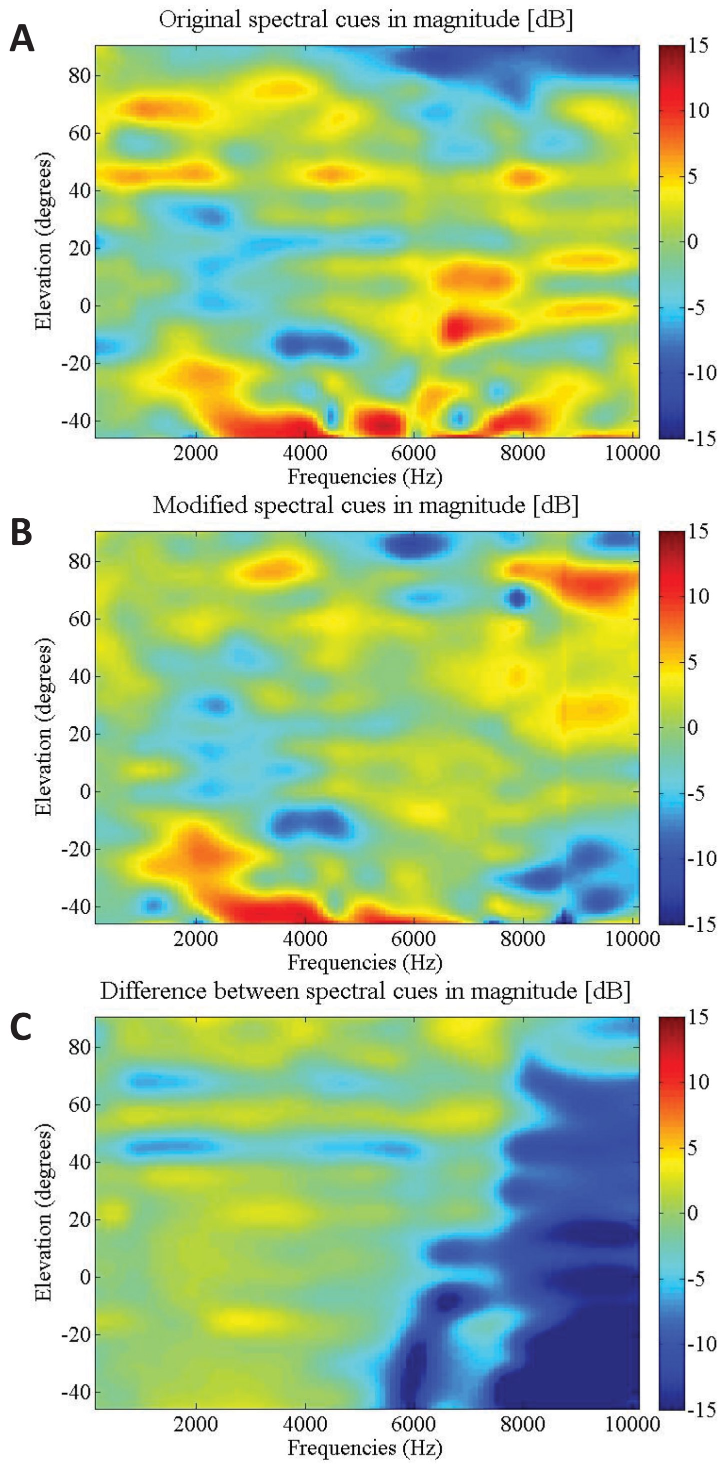


Figure 2. A) Head-related transfer functions without molds, with molds (B), and the difference between the two (C). Note the elevation-dependent attenuation of frequencies above 6000 Hz.

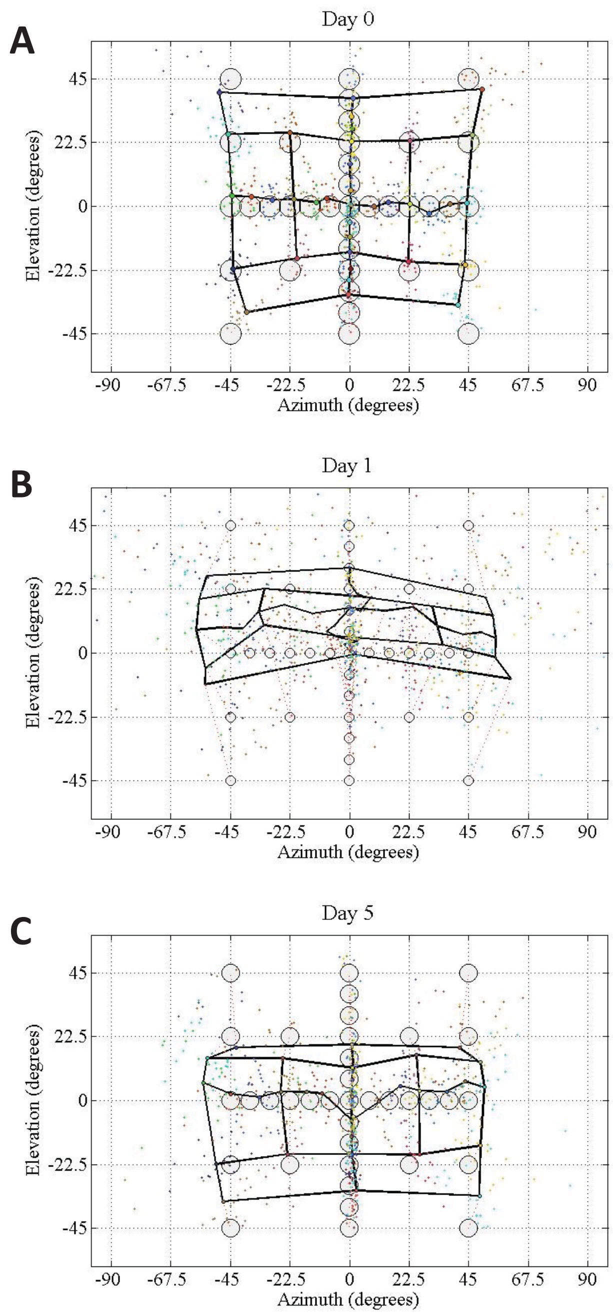


Figure 3. A) Sound localization performance before inserting the molds. Grey circles mark the actual loudspeaker positions. Dots represent the mean performance of different participants. The black grid shows the grand mean perceived locations. B) Elevation perception is biased when the molds are inserted, but gradually returns to normal after four training sessions (C).

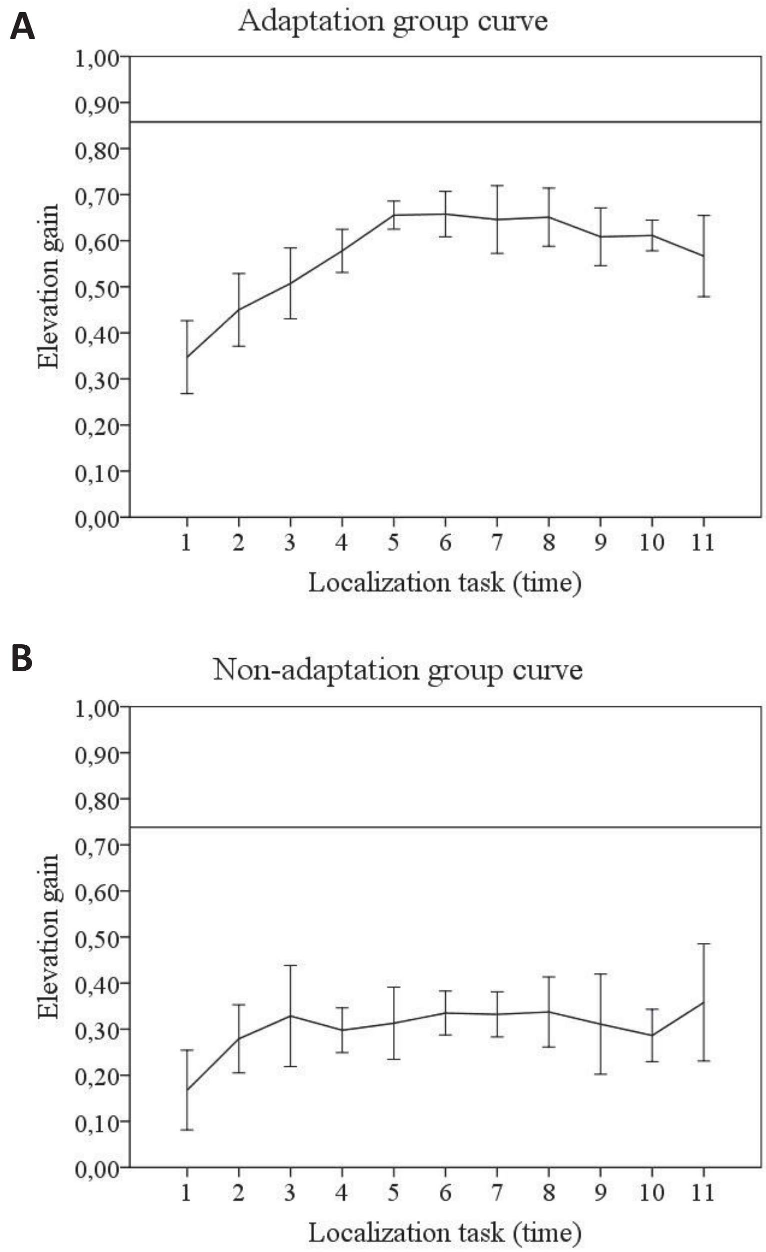
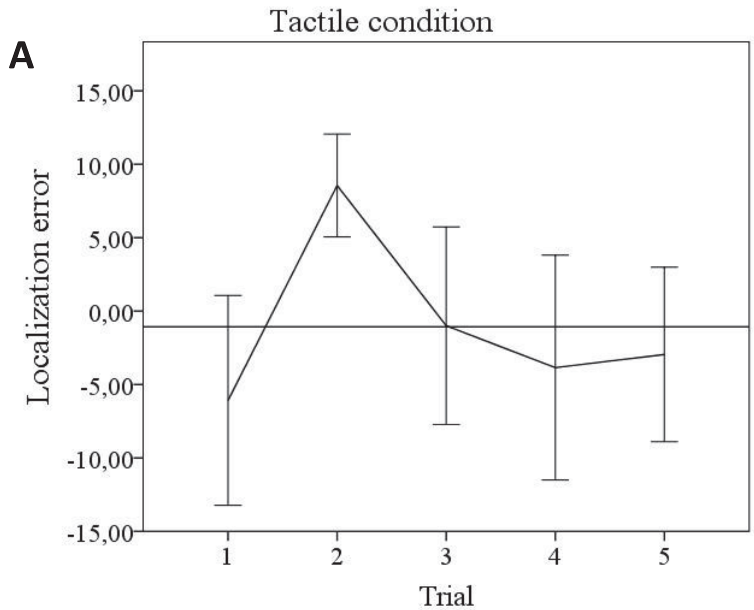


Figure 4. A) The average performance across participants in each localization test while wearing the molds followed a quadratic function for the participants who adapted to the molds, compared to those who did not (B). The black line represents the mean elevation gain during baseline performance (before the molds). Error bars represent standard errors adjusted with the grand mean.



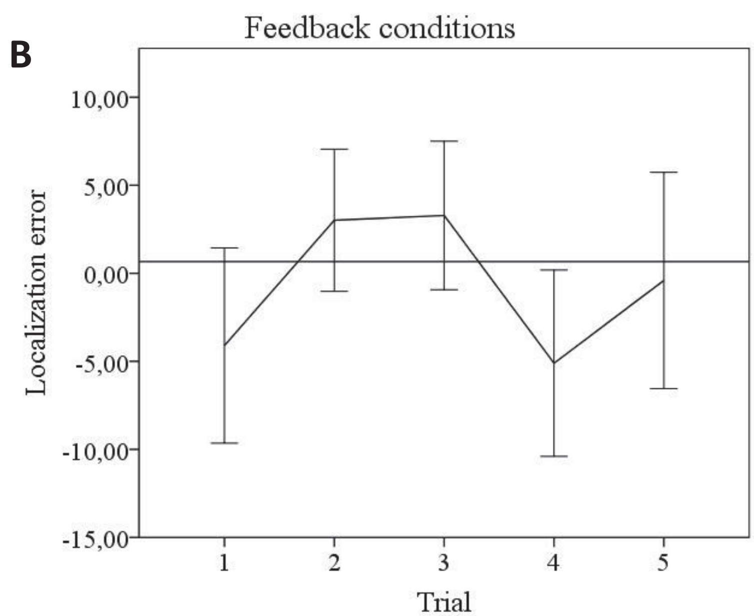


Figure 5. A) Trial by trial elevation gain for the first five trials during test localization task for the tactile condition, and for the control, spectral and visual groups combined (B). The black line represents the mean elevation gain for the first five trials. Error bars represent standard errors adjusted with the grand mean.

Conclusion

La présente étude a mesuré l'adaptation aux changements induits aux indices spectraux en ciblant trois objectifs : 1) répliquer les méthodes de Hofman, van Riswick et van Opstal (1998), 2) examiner les mécanismes perceptuels responsables du transfert d'un ensemble de HRTFs à un autre, et 3) déterminer la permanence de l'adaptation. Bien que certains participants ne se soient pas adaptés pendant la durée de l'étude, les résultats ont révélé que la majorité des participants s'adaptait aux nouveaux HRTFs en l'espace de quatre séances d'entraînement. Deux raisons pourraient justifier les données divergentes : soit les modifications aux HRTFs étaient trop extrêmes pour qu'une adaptation soit possible, soit les participants auraient nécessité davantage de séances d'entraînement afin de s'adapter aux prothèses. Les données viennent néanmoins supporter la plasticité cérébrale en contexte de localisation spatiale sur l'axe de l'élévation, tout en soulignant les contraintes de cette plasticité.

Quant aux rétroactions perceptuelles, les résultats ne permettent pas de vérifier les mécanismes responsables du transfert d'un ensemble de HRTFs à un autre, faute du nombre de participants dans chaque groupe expérimental. Pour cette raison, les prochaines études devront utiliser un plus grand nombre de participants. Également, certaines pistes devront être approfondies par d'autres recherches. Entre autres, il serait judicieux pour la condition spectrale d'employer une randomisation spectrale plus prononcée que celle utilisée dans la présente étude. En effet, il est probable que le transfert d'un ensemble de HRTFs n'ait pas été influencé par la manipulation perceptuelle considérant la similarité de la randomisation spectrale aux vrais indices spectraux. La condition tactile quant à elle nécessite une meilleure mise au point, compte tenu des performances à la tâche contrôle avec écouteurs étant significativement différents de ceux de la condition contrôle sans écouteurs. Enfin, les résultats ne permettent pas de déterminer à quel moment le transfert d'un ensemble de HRTFs à l'autre se produit. Toutefois, il est suggéré d'inclure les différences de location des différents stimuli dans les futures analyses, élément qui pourrait faciliter ou contraindre le transfert, avant de conclure que le transfert s'effectue de manière instantanée telle que décrit par Hofman, van Riswick et van Opstal (1998).

Finalement, la permanence de l'adaptation appuie les conclusions de Hofman, van Riswick, et van Opstal (1998), corroborant l'hypothèse de la durabilité de la plasticité cérébrale. D'autres études pourront se pencher sur la permanence de telles adaptations à plus long terme que ceux examinés dans la présente étude, soit en complétant de nouveau la tâche après des périodes de trois et six mois.

Depuis l'étude de Hofman, van Riswick, et van Opstal (1998), bien peu de recherches ont été menées sur la plasticité de la localisation spatiale, particulièrement sur l'axe de l'élévation. La présente étude se voulait répondre à certaines questions soulevées par ces auteurs, et a soulevé plusieurs interrogations à son tour. Entre autres, il serait intéressant de savoir si les résultats obtenus peuvent être généralisés à une autre population que les étudiants. De plus, une comparaison entre les musiciens et non-musiciens est également pertinente : des analyses subséquentes à la présente étude restent d'ailleurs à venir. Une piste intéressante à poursuivre serait de découvrir davantage concernant les effets physiologiques de l'adaptation aux prothèses de silicone sur le cortex auditif à l'aide d'imagerie cérébrale. À ce propos, un tel projet sur l'axe de l'azimuth est présentement en cours au Laboratoire international de recherche sur le cerveau, la musique et le son (BRAMS). Ainsi, les futures études permettront de déterminer précisément les conditions de plasticité cérébrale liée à la localisation spatiale des sons, à savoir les conditions idéales d'adaptation et de rappel, afin d'être bénéfique à tout type d'apprentissage confondu.

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Annexe I

See English below

Adaptation aux changements des indices spectraux de l'audition spatiale chez l'humain.

Bonjour,

Le Laboratoire international de recherche sur le Cerveau, la Musique et le Son (BRAMS) est actuellement à la recherche de participants âgés de 18 à 35 ans pour une étude de localisation spatiale.

L'étude consiste à porter des prothèses de silicone aux oreilles pour une période approximative de 10 jours. Durant cette période, le participant devra se présenter quotidiennement au BRAMS afin d'effectuer des tâches de localisation auditive d'une durée de 30 minutes. Cette expérience se déroulera dans la salle hémi-anéchoique du BRAMS.

Les individus ayant des troubles de l'audition ou portant un implant cochléaire ne pourront prendre part à la recherche. Les personnes ayant des perçages aux oreilles ailleurs qu'aux lobes d'oreilles (p.ex. conque/ tracus), ou allergiques au latex et à la silicone ne pourront participer à l'étude.

Une compensation financière vous sera remise pour votre participation à cette expérience, pour un montant approximatif total de 110$.

L'expérience se déroule au BRAMS (Université de Montréal) situé au 1430 boul. Mont-Royal, à quelques pas de la station Édouard-Montpetit.

Si vous êtes intéressé(e), fournissez votre nom, prénom, courriel et numéro où vous joindre, à Valérie :

[redacted]

N'hésitez pas à me contacter si vous avez des questions ou désirer plus d'informations.

Valérie Aubrais

sous la supervision du Pr. Marc Schönwiesner

Adaptation to spectral cue changes in spatial hearing in humans.

Hi,

The International Laboratory for Brain, Music, and Sound Research (BRAMS) is currently looking for participants aged between 18 and 35, with normal hearing, to take part in a spatial localization study.

The study consists in wearing ear silicon molds for approximately 10 days. During this period of time, the participant will be asked to come <u>daily</u> to the BRAMS to complete auditory localization tasks for 30 minutes. This experiment will be completed in the BRAMS hemi-anechoic room.

Individuals with auditory problems or using a cochlear implant cannot take part in the study. Individuals with ear piercings in areas other than earlobe (f. ex. conch, tracus), or with allergies to latex and silicon cannot participate either.

A monetary compensation will be offered, for an approximate total of 110$.

BRAMS is located in 1430 boul. Mont Royal, Université de Montréal, a mere few minutes from Édouard-Montpetit station.

If you are interested in taking part in this study, please send your family name, name, e-mail and phone number to Valerie :

[redacted]

Do not hesitate to contact me if you have any questions or require more information.

Valerie Aubrais
Supervisor : Pr. Marc Schönwiesner

Annexe II

FORMULAIRE DE CONSENTEMENT

Titre de la recherche : Adaptation aux changements des indices spectraux de l'audition spatiale chez l'humain.

Chercheur : Valérie Aubrais, BRAMS, Département de Psychologie, Université de Montréal

Directeur de recherche : Marc Schönwiesner, BRAMS,
Département de Psychologie, Université de Montréal

A) RENSEIGNEMENTS AUX PARTICIPANTS

1. Objectifs de la recherche.

L'humain utilise des indices spectraux afin de localiser les sons sur l'axe vertical. Ce projet de recherche vise à mieux comprendre les processus sous-jacents à ces indices spectraux.

2. Participation à la recherche

Ce projet de recherche se déroulera au laboratoire BRAMS de l'Université de Montréal. Votre participation consistera en plusieurs séances d'environ 30 minutes, sauf les deux premières séances qui dureront approximativement 1 heure.

La première séance, divisée en deux rencontres, se déroulera comme suit :

– Vous devrez tout d'abord remplir un **questionnaire** de renseignements personnels.

– Vos capacités auditives seront testées grâce à un **test audiométrique** d'une durée approximative de 15 minutes.

– Vous serez ensuite invité(e) à vous asseoir dans un fauteuil installé dans la salle hémianéchoïque (sans écho).

– La première partie de l'expérience, d'une durée approximative de 5 minutes, consistera en une série d'**enregistrements sonores** effectués à l'aide de microphones préalablement installés dans votre conduit auditif (installation totalement indolore, similaire à l'insertion de bouchons d'oreilles). Les sons seront émis à l'aide de haut-parleurs installés à une distance moyenne de 90 cm du fauteuil, à une intensité confortable (sans aucun danger pour l'oreille humaine).

– Une fois ces enregistrements effectués vous serez invité(e) à participer à deux **tâches de localisation auditive**. Chaque tâche durera environ 15 minutes. Nous installerons sur votre tête un pointeur laser à l'aide d'un bandeau élastique ainsi qu'un dispositif nous permettant d'enregistrer les positions de votre tête. Lors des tests, différents sons vous seront présentés à l'aide de haut-parleurs ou d'écouteurs et vous devrez déplacer le pointeur laser en tournant la tête dans la direction d'où le son semble provenir.

– Nous vous installerons ensuite des **prothèses** de silicone qui changeront la forme de vos oreilles externes. Vous serez alors invité(e) à procéder une seconde fois à la série **d'enregistrements sonores** avec les microphones installés dans votre conduit auditif (5 minutes), puis aux **tâches de localisation auditive** (15 minutes).

Par la suite, nous fixerons avec vous des rendez-vous pour les séances suivantes, à **tous les jours jusqu'à adaptation** (approximativement 10 jours). Chaque séance, vous serez invité(e) à accomplir la **tâche de localisation auditive**, pour une durée approximative de 15 minutes, en plus d'une tâche d'**entraînement** pour vous permettre de vous adapter à vos nouveaux indices.

À la **dernière séance**, vous serez invité(e) à procéder à la **tâche de localisation auditive** (10 minutes). Nous enlèverons ensuite les prothèses de silicone, puis vous serez invité(e) à accomplir la **tâche** de nouveau (15 minutes).

Si vous êtes intéressé(e), nous aimerions pouvoir vous contacter dans l'éventualité d'une seconde vague d'étude ayant une procédure de recherche similaire, afin d'examiner l'effet de permanence de l'adaptation.

3. Confidentialité

Les renseignements que vous nous donnerez demeureront confidentiels. Seuls les renseignements nécessaires à la bonne conduite du projet de recherche seront recueillis. Chaque participant à la recherche se verra attribuer un numéro et seul le chercheur principal ou la personne mandatée à cet effet auront la liste des participants et des numéros qui leur auront été attribués. De plus, les renseignements seront conservés dans un classeur sous clé situé dans un bureau fermé. Aucune information permettant de vous identifier d'une façon ou d'une autre ne sera publiée. Ces renseignements personnels seront détruits 7 ans après la fin du projet. Seules les données ne permettant pas de vous identifier seront conservées après cette date. Advenant la publication des résultats, aucune information pouvant vous identifier ne sera divulguée.

4. Avantages et inconvénients

En participant à cette recherche, vous pourrez contribuer à l'avancement des connaissances sur le système auditif et l'adaptation à de nouveaux indices liés à la localisation des sons. Votre participation à la recherche pourra également vous donner l'occasion de mieux vous connaître du point de vue de l'audition.

Les prothèses de silicone seront installées de manière discrète sur l'oreille externe. Les prothèses sont incolores, donc presque imperceptibles à l'œil. Les prothèses viendront changer la perception du son, mais seulement sur l'axe d'élévation du son : ainsi, les prothèses ne viendront pas perturber votre perception azimuth (gauche-droite). Vous n'encourez donc aucun danger dans l'accomplissement de tâches quotidiennes, telles que la circulation routière. Vous recevrez des instructions d'entretien des prothèses afin d'assurer votre confort et le bon déroulement de l'étude.

Les prothèses pourraient vous déranger le temps de s'y habituer (inconfort, démangeaisons) et de s'adapter aux nouvelles élévations des sons. Il est possible que l'expérience vous importune par sa longueur, ou par la répétitivité des tâches demandées. Des pauses sont prévues à l'intérieur des séances de tests.

5. Droit de retrait

Votre participation est entièrement volontaire. Vous êtes libre de vous retirer en tout temps par avis verbal, sans préjudice ou conséquences négatives et sans devoir justifier votre décision. Si vous décidez de vous retirer de la recherche, vous pouvez communiquer avec le chercheur, au numéro de téléphone indiqué à la dernière page de ce document. Si vous vous retirez de la recherche, les renseignements qui auront été recueillis au moment de votre retrait seront détruits.

6. Indemnité

Vous recevrez une compensation financière de 50 $ pour le port des prothèses pendant une période de 10 jours. À chaque séance, vous recevrez également un montant de 5 à 10 $ par séance, selon la durée de la rencontre. Le montant total approximatif est de 110 $ pour la durée de l'étude.

B) CONSENTEMENT

Je déclare avoir pris connaissance des informations ci-dessus, avoir obtenu les réponses à mes questions sur ma participation à la recherche et comprendre le but, la nature, les avantages, les risques et les inconvénients de cette recherche.

Après réflexion, je consens librement à prendre part à cette recherche. Je sais que je peux me retirer en tout temps sans préjudice et sans devoir justifier ma décision.

Signature : ____________________________ Date : _________________________

Nom : ________________________________ Prénom : _______________________

Je déclare avoir expliqué le but, la nature, les avantages, les risques et les inconvénients de l'étude et avoir répondu au mieux de mes connaissances aux questions posées.

Signature du chercheur____________________ Date : ____________________________
(ou de son représentant)

Nom : _________________________________ Prénom : __________________________

Pour toute question relative à la recherche, ou pour vous retirer de la recherche, vous pouvez communiquer avec Valérie Aubrais, étudiante à la Maîtrise, au numéro de téléphone suivant : [redacted] ou à l'adresse courriel suivante : [redacted]. Vous pouvez également contacter Marc Schönwiesner, Ph. D. : [redacted] ou [redacted].

Toute plainte relative à votre participation à cette recherche peut être adressée à l'ombudsman de l'Université de Montréal, au numéro de téléphone [redacted] ou à l'adresse courriel [redacted]. **(L'ombudsman accepte les appels à frais virés).**

Un exemplaire du formulaire de consentement signé doit être remis au participant.